New Experimental Highlights from PITZ

The beam already knows what emittance it should deliver, we just have to measure it!

Content:
- measurement setup
- cathode laser
- different guns
- longitudinal phase space
- transverse projected emittance
- cathode studies
- future upgrades of the facility
The PITZ collaboration

Colleagues actively participating in measurements / new design:

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******* now at JLAB, Newport News

Present layout of PITZ

This setup was used for the measurements to be presented:

- **momentum + momentum spread**
- **transverse projected emittance**
- **dark current**
- **1.5 cells, Cs₂Te cathode**
- **High energy part**
- **Low energy part**
- **booster**
- **gun + solenoids**

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XFEL Meeting, Hamburg

October 10th, 2007
Present layout of PITZ
**Photo cathode laser**

Schematics of the diode-pumped Nd:YLF photo cathode laser system

Beamline to photo cathode

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Photo cathode laser properties

• **longitudinal profile:**
  
  - FWHM = 20.22 ps; \( t_1 = 6.58 \text{ ps}; t_2 = 6.67 \text{ ps}; \) FTmod = 6.52%

  ![Longitudinal profile graph](image)

<table>
<thead>
<tr>
<th></th>
<th>FWHM [ps]</th>
<th>rise / fall [ps]</th>
<th>RMS [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oct. '06</td>
<td>~18</td>
<td>6 – 8</td>
<td>~0.5</td>
</tr>
<tr>
<td>now</td>
<td>~20</td>
<td>6 – 8</td>
<td>~0.35</td>
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• **transverse profile:**
  
  - \( \sigma_{x,y} : 0.05 \rightarrow 0.6 \text{ mm} \)
  
  - RMS = 7.5%

• **energy stability:**
  
  - \(<\text{RMS}_i> >= 2.0 \% \)
  
  - RMS(mean \(i\)) = 1.3 \%

• **pointing stability:**
  
  - \(<\text{RMS}_i> = 0.033 \text{ mm} \)
  
  - \(<\text{RMS}_i> = 0.032 \text{ mm} \)
**Guns, Gradients, Dark Currents**

- **Gun 3.1**
  - characterized @ ~40MV/m in Oct. ’06
  - spare gun for FLASH

- **Peak and average power:**
  - 3.5 MW, 900 µs, 10 Hz
  - 31.5kW av. power, 0.9% duty cycle

- **Dark current:**
  - Max.: 250-300 µA

- **Gun 3.2**
  - characterized @ ~60MV/m in summer ’07
  - first experience with long RF at 60 MV/m

- **Peak and average power:**
  - standard run: ~6.7 MW, 10Hz, 140µs
  → ~9.4 kW

- **Dark Current:**
  → very high ! → possible reason: cavity fabrication error in cathode region
Longitudinal phase space for gun3.2

Problem with maximum momentum:
- measured momentum lower than expected from RF power readings
- possible reason:
  → power measurements

Momentum and momentum spread downstream of the gun:

Momentum and momentum spread downstream of the booster:
Projected Emittance Measurements: 
\[ \mathcal{E}_{x,n} = \beta \gamma \cdot X_{rms} \cdot X'_{rms} \]

- \( X_{rms} \) - RMS size of full beam at EMSY station (e.g. \( z = 4.3 \text{ m} \))
- \( X'_{rms} = \frac{1}{L} \sum_{i=1}^{n} w_i \left( X_{beamlet} \right)_i^2 \left/ \sum_{i=1}^{n} w_i \right. \) - uncorrelated local divergence
- \( X_{beamlet} \) - RMS size of the beamlet image
- \( L \) - distance from slit location to screen for beamlets

• Current standard procedure:
  - take 11 equidistant beamlets over the full beam size
  - use 10 µm slit opening
  - ultimate resolution (current setup):
    \( \rightarrow 36 \mu \text{m} \times 15.4 \mu \text{rad} \)
  - use camera with 12 bit signal depth for beamlet measurements
Emittance results October 2006

Gun gradient: ~ 43 MV/m
Gun phase: \( \Phi_{\text{gun}} = \Phi_{\text{ref}} - 2 \) deg
Momentum from gun: ~ 5.0 MeV/c

Booster phase: \( \Phi_{\text{booster}} = \Phi_{\text{ref}} - 5 \) deg
Total beam momentum: 12.8 MeV/c

\\[ \sqrt{X Y} \text{ EMSY3 - 9.9m} \]
\\[ \sqrt{X Y} \text{ EMSY2 - 6.6m} \]
\\[ \sqrt{X Y} \text{ EMSY1 - 4.3m} \]

\[ \Phi_{\text{gun}} = \Phi_{\text{ref}} - 2 \) deg \]
\[ \Phi_{\text{booster}} = \Phi_{\text{ref}} - 15 \) deg

\( \Rightarrow \text{for } 43 \text{ MV/m we obtained} \)
\[ \varepsilon_{x,n} = 1.32 \pm 0.11 \text{ mm mrad} \]
\[ \varepsilon_{y,n} = 1.43 \pm 0.17 \text{ mm mrad} \]

\( \Rightarrow \text{emittance strongly increases with distance from booster} \)
Expectations for 60 MV/m

What's new in new ASTRA (spring '07)?
- solved convergence problem of space charge routine for very short bunches → important during emission,
- included new parameter to control time steps → important when bunch just left cathode

Slice emittance (5ps)
Slice emittance (7ps)

1.28 mm mrad (position of EMSY1)

Slice emittance, [mm mrad]

Emittance, [mm mrad]

Transverse slice emittance at z=4.3m

Slice emittance (5ps)
Slice emittance (7ps)

Slice emittance, [mm m rad]

z-<z>, mm

Slice emittance, [mm m rad]

"old" ASTRA, 5ps rise/fall time
new ASTRA, 5ps rise/fall time
new ASTRA, 7ps rise/fall time

(optimized for current booster position)
Cathode: # 90.1
Gun gradient: ~ 60 MV/m
Gun phase: $\Phi_{\text{gun}} = \Phi_{\text{ref}}$
Momentum from gun: ~ 6.44 MeV/c

Booster phase: $\Phi_{\text{booster}} = \Phi_{\text{ref}}$
Total beam momentum: 14.5 MeV/c

➤ for ~60 MV/m we obtained
$\varepsilon_{x, n} = 1.25 \pm 0.19$ mm mrad
$\varepsilon_{y, n} = 1.27 \pm 0.18$ mm mrad

@1nC

for 100 % RMS emittance!

➤ good agreement with prediction from ASTRA

preliminary analysis

Emittance for 1 nC and 60 MV/m
x-x´-phase space distribution for the best emittance measurement, purely reconstructed from subsequent beamlet measurements:

- Emittance calculated purely from beamlet measurements, 100 % of data
  \( \varepsilon_n = 1.1 \text{ mm mrad} \)

- Cut at 5% of max. amplitude (i.e. 6.5% of “charge”) [reasons: noise, gain, sensitivity, bit depth, …]
  \( \varepsilon_n = 0.69 \text{ mm mrad} \)

Reminder: This \( \varepsilon_n \neq 1.25 \text{ mm mrad} \) because the separately measured beam size at the slit position is NOT taken into account here.

Projected emittance is reduced by 37 % !

ASTRA: - 5% in particles \( \Rightarrow \) -38% in proj. emittance

For 95% RMS \( \Rightarrow \) \( \varepsilon_{x,y,n} \approx 0.8 \text{ mm mrad} \)
XPS investigations on photo cathodes

Te 3d spectrum for **fresh** cathode #90.1

- **fresh cathode:**
  - dominant peaks for both spin-orbit couplings corresponding to Te$^{-2}$ ($\text{Cs}_2\text{Te}$)
  - small amounts of Te$^0$

Te 3d spectrum for **used** cathode #92.1

- **used cathode:**
  - dominant peaks for both spin-orbit couplings corresponding to Te$^0$ (metallic tellurium)
  - only small amounts of Te$^{-2}$ ($\text{Cs}_2\text{Te}$)

**Confirmation from survey scan:**

- Te$^{+6}$ visible ($\text{TeO}_3$) on fresh cathodes but no oxidized states on used cathodes

→ QE degradation during operation most probable related to change in chemical composition

→ transition from $\text{Cs}_2\text{Te}$ to metallic Te
Thermal emittance measurements

\[ \varepsilon_{th} = \sigma_{\text{cathode}} \sqrt{\frac{2E_{\text{kin}}}{3m_0c^2}} \]

\[ \varepsilon_{meas} \approx \sqrt{\varepsilon_{th}^2 + \varepsilon_{SC}^2 + \varepsilon_{RF}^2} \]

measure \( \varepsilon_{th} \) vs. \( \sigma_{\text{cathode}} \) for low charge (\( \leq 6\mu\text{C} \)) and short pulse length (\( \sigma_{\text{laser}} \approx 3-4\text{ps} \)) \( \Rightarrow E_{\text{kin}} \)

Expected \( E_{\text{kin}} \) for \( \text{Cs}_2\text{Te} \) cathode and \( 262\text{ nm laser:} \) 0.55 eV (this does not consider: field on cathode, change of cathode properties during operation)

\begin{itemize}
  \item Error bars not small, but
  \begin{itemize}
    \item there is increasing \( E_{\text{kin}} \) with gradient at cathode!
    \item different cathodes can behave differently!
    \item \( E_{\text{kin}} \approx 1.4 \text{ eV} @E_0=60\text{MV/m} \) \( \Rightarrow \) 2 x larger than model
    \item for \( \sigma_{\text{cathode}}= 0.35\text{mm} \) \( \Rightarrow \varepsilon_{th} = 0.47 \text{ mm mrad (\( \sim 50\% \))} \)
  \end{itemize}
\end{itemize}

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Future upgrades at PITZ

**this autumn:**
- install improved laser system (20 ps FWHM, rise/fall time ≤ 2 ps)
- install improved dispersive arm downstream of booster (HEDA1) → slice emittance measurements
- condition new gun cavity to 60 MV/m

**2008:**
- install new CDS booster and tomography section
- start experimental optimization for European XFEL baseline parameters

**layout:**
- install new CDS booster and tomography section
- start experimental optimization for European XFEL baseline parameters
Work to be done, problems during run

- **Dark current from cavity 3.2**: although dark current was reducing during conditioning/operation → **still very high at 60 MV/m**. We assume that one main reason is a **fabrication error** which did not happen again at later cavities. **New cavity 4.2 was cleaned with CO₂ and conditioning will start on a separate test stand in November 2007.**

- **Life time of photo cathodes**: only up to ~1 week in last run period. Reason not clear. Might be related to high **level of dark current**, may be in addition related to **Flour impurities in the vacuum system.**

- **Comparison simulation ↔ measurements**: although value for absolute minimum emittance agrees very well, **dependencies on operation parameters** (e.g. energy gain in booster) are very different. → studies have to be continued.

- **Laser system**: up to now rise/fall time of 6-8 ps was possible → one of the reasons why **tails** in distributions dominate emittance number. This autumn, a **new laser system** will be installed which should allow 2 ps rise/fall time. **Stability and usability** of the new system has to be observed during real operation.
Work to be done, problems during run (2)

- **RF system (llrf and total power):**
  - up to now only feed-forward is possible (no regulation) → instabilities.
  - currently, 60 MV/m only reached with saturated klystron → no hat-space for regulation.
  → Several approaches ongoing to allow llrf regulation and higher total power at the gun. (klystron with > 10 MW ???)

- **„Core emittance“:** to measure / optimize it → particles in tails of PHASE SPACE distributions have to be cut (not in coordinate space). This measurements require very long & stable measurement time → can only be done for individual cases at the moment. Next year we plan to install a tomography module which allows phase space tomography as standard measurement operation.

- **Slice emittance:** what finally counts is slice emittance in high current part of electron bunch. According to our current knowledge, the only way to measure it with the required accuracy is the usage of an RF deflector. E.g. also LCLS is intensively using their RFD to characterize their injector. Therefore, the development of the RFD for PITZ (e.g. pre-test of XFEL version) should be continued.
Outlook

• Optimize injector for XFEL baseline parameters:
  Ingredients:
  – laser upgrade this year
  – the installation of the CDS booster next year
  – extension of the diagnostics beamline now and in next year(s)

→ we will be able to study the evolution of the emittance for the full XFEL baseline parameters:
  - do experimental optimization
    (full variation of experimental parameters, systematic cathode studies, ..., 1-2 years)
  - in parallel also requires further development of the simulations.
Summary

• Gun3.1 characterized at ~40 MV/m:
  – operated with up to 3.5MW, 900µs RF, 10Hz
  – $\varepsilon_x, n = 1.32 \pm 0.11$ mm mrad
  – $\varepsilon_y, n = 1.43 \pm 0.17$ mm mrad
  \@1nC, (100% RMS)

• Gun3.2 characterized at ~60 MV/m:
  – operated with up to 6.7MW, 140 µs RF, 10Hz
  – $\varepsilon_x, n = 1.25 \pm 0.19$ mm mrad
  – $\varepsilon_y, n = 1.27 \pm 0.18$ mm mrad
  \@1nC, (100% RMS)
  \rightarrow for 95%-RMS: $\varepsilon_{x,y,n} \approx 0.8$ mm mrad !!
  \rightarrow first demonstration of emittance required for European XFEL
  – thermal emittance: $E_{kin} \approx 1.4$ eV
  \rightarrow $\varepsilon_{th} = 0.47$ mm mrad (~50%)

• observed change of chemical composition of Cs$_2$Te cathodes using XPS
• upgrades at PITZ are ongoing \rightarrow e.g. new laser in 2007